

Next-Generation Nano- and Micro-Scale-Based Power and Sensor Technologies: A New Perspective on Dual Space-Terrestrial Applications

presented at

***ASME 16th International Conference on Nanochannels, Microchannels, and Minichannels 2018
Dubrovnik, Croatia***

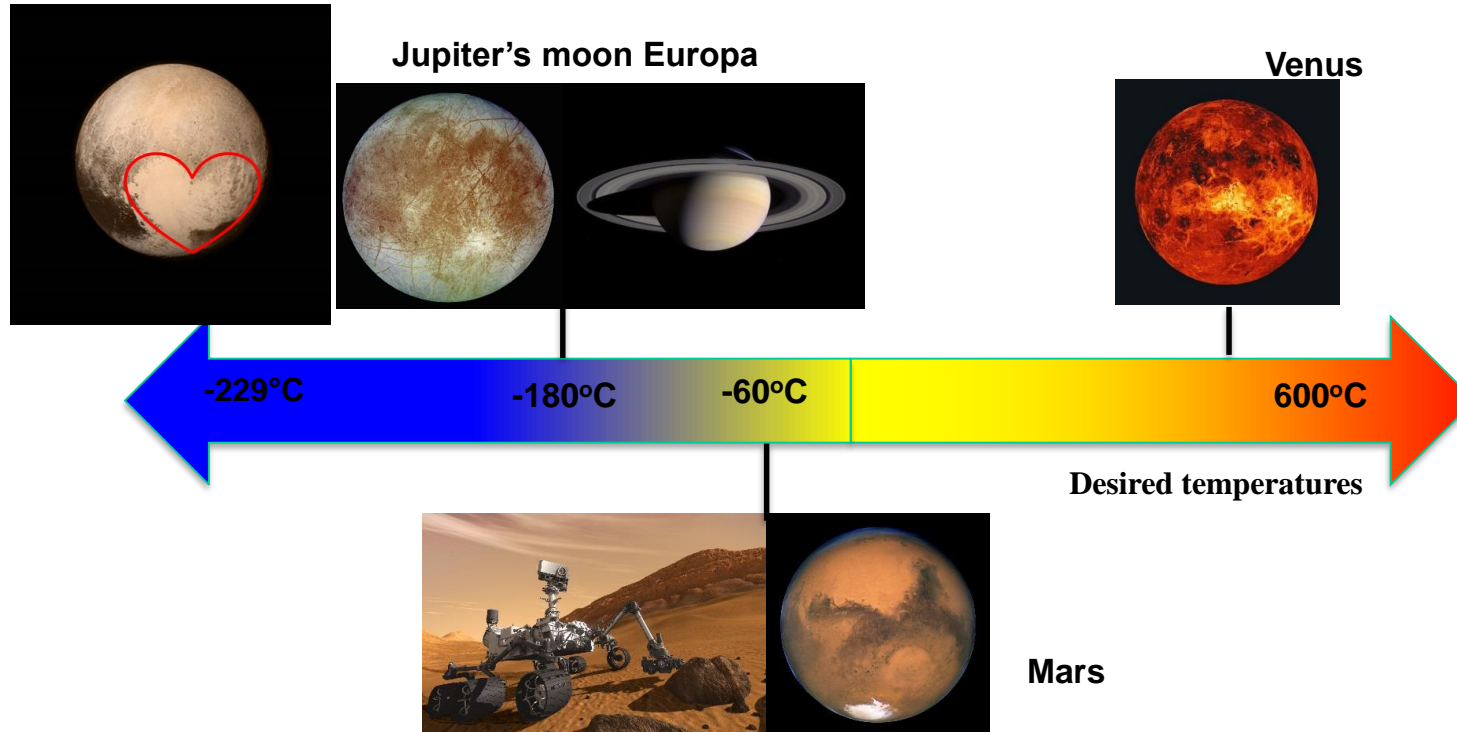
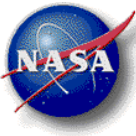
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11 June 2018

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Extreme Environments



Extreme environmental conditions for planetary missions (e.g., temperatures, gravity, thermal shock, radiation, and chemical attack)

NASA Science Exploration Missions Need for Both Solar & Radioisotope Power Systems (RPS)

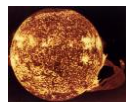
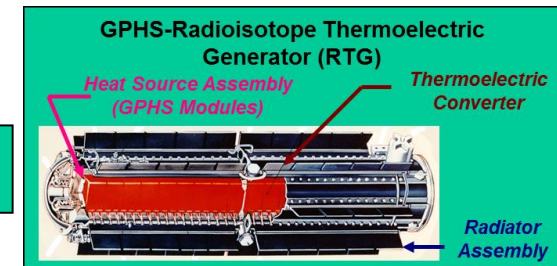


Solar power systems serve a *critical* role in the scientific exploration of the near-Earth solar system

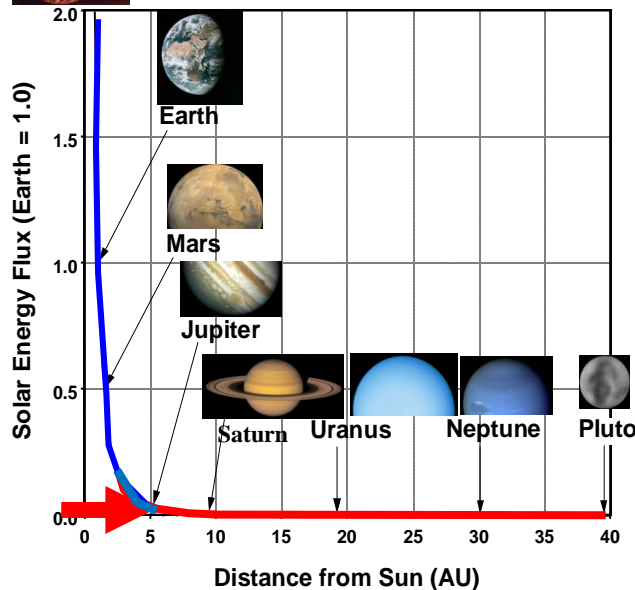
- Moderate power levels up to 100 kW
- Operations dependent on distance and orientation with respect to Sun

Radioisotope power systems (RPS) serve a *critical* role in the scientific exploration of the deep-space solar system

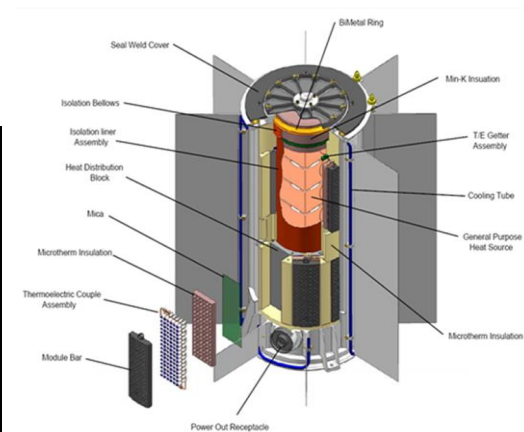
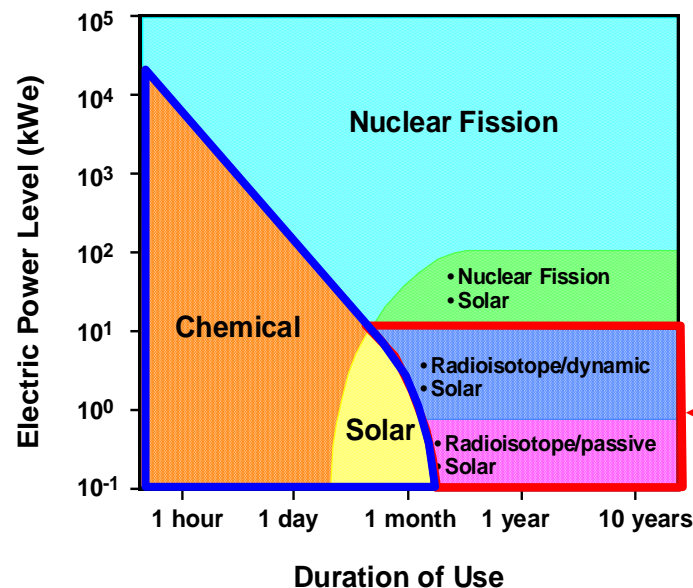
- Low to moderate power levels (~100 W - 1 kW) for more than several months
- Operations independent of distance and orientation with respect to Sun



Inherent limitation of solar power



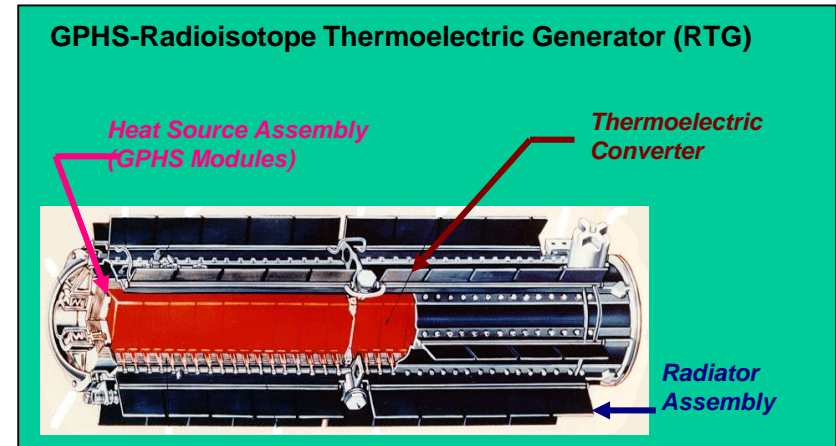
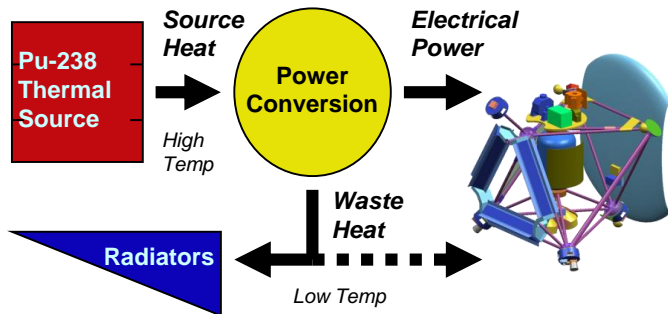
Best candidates for maximizing specific power



Multi-Mission RTG

Overview of a Radioisotope Power System

- **High grade heat** produced from natural alpha (a) particle decay of Plutonium (Pu-238)
 - 87.7-year half-life
 - Heat source temperature ~ 1300 K
- **Portion of heat energy converted to electricity** via passive or dynamic thermal cycles (6%-35%)
 - Thermoelectric (existing & under development)
 - Stirling (under development)
 - Thermophotovoltaic, Brayton, etc. (future candidates)
- **Waste heat** rejected through radiators or a portion can be used for **thermal control of spacecraft subsystems**



Performance characteristics

- Specific power (W/kg) → Direct impact on science payload
- T/E efficiency → Reduces PuO₂ needs
- Power output → Supports diverse mission profiles

RTGs used successfully on 27 spacecrafts since 1961

- 11 Planetary (Pioneer 10 & 11, Voyager 1 & 2, Galileo, Ulysses, Cassini, New Horizons)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP), 3 Mars Surface (Viking, MSL/Curiosity)

CASSINI Spacecraft to Saturn (1997-2017)

- Liquid Rivers & Lakes of Ethane & Methane Over Frozen Water
 - Ethane and Methane “Rains” in Atmosphere (Pressure Slightly Higher than ~1 atm)
 - Methane Atmosphere ~5% Methane – Geologic Processes Replacing Methane
- Flew Cassini spacecraft into Saturn on 15 September 2017 (Final Dive)
 - **Grand Finale** - 22 passes between ~2500-km gap between inner rings / Saturn’s upper atmosphere
 - Velocity during inner ring passages 121,000-126,000 kmph
 - RTG Power Degradation shown below – 32% over
 - Lost Cassini signal 1400 km above clouds

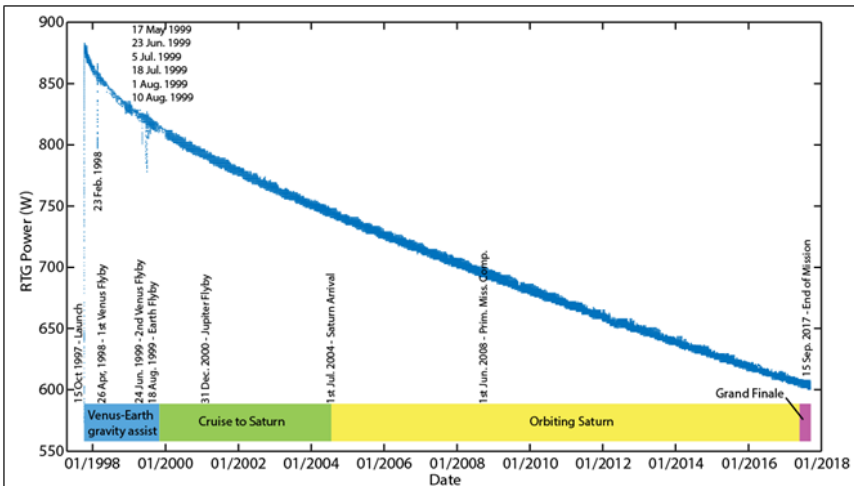
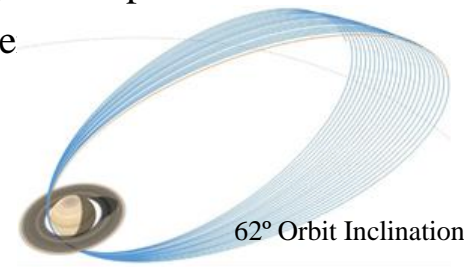
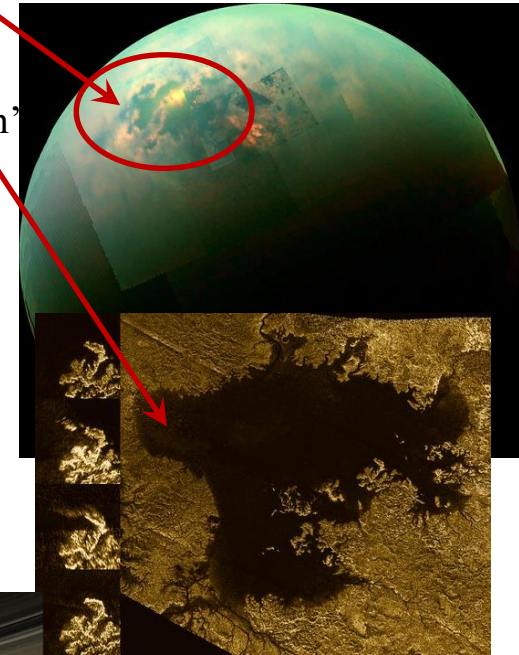


Fig. 1. Cassini recorded power output telemetry data over the entire mission between launch and EOM. The data is divided into four mission phases: The Venus-Earth gravity assist, the cruise to Saturn, orbiting Saturn



**RTG Power Made this All Possible
SiGe TE Materials**

New Horizons to Pluto (2006-Continuing)

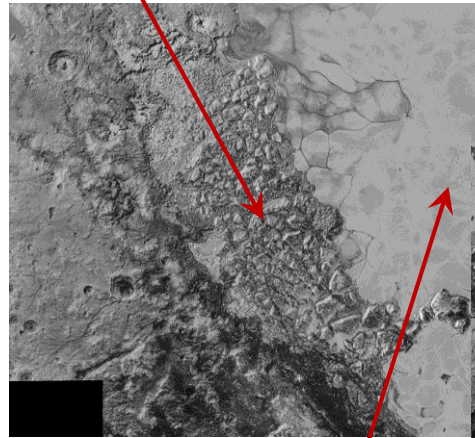


Heart of Pluto

With Love,
Pluto

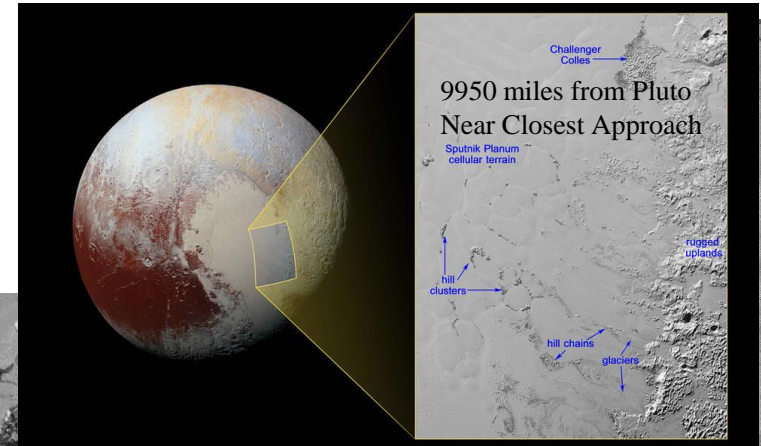
476,000 miles from Pluto

Large region of jumbled,
broken terrain



Vast, Icy Plain – Sputnik Planum
50,000 miles from Pluto

300 mile wide image, smallest features
0.5 mile wide



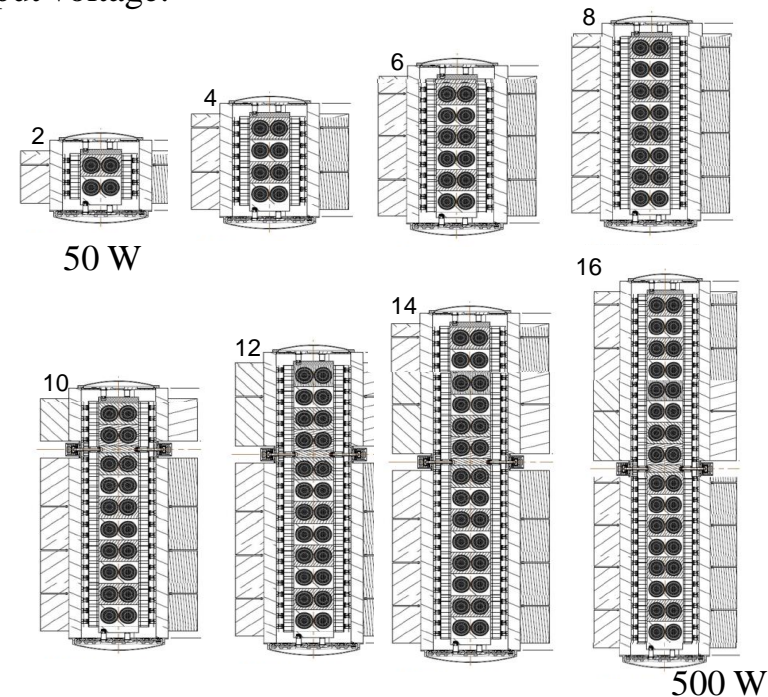
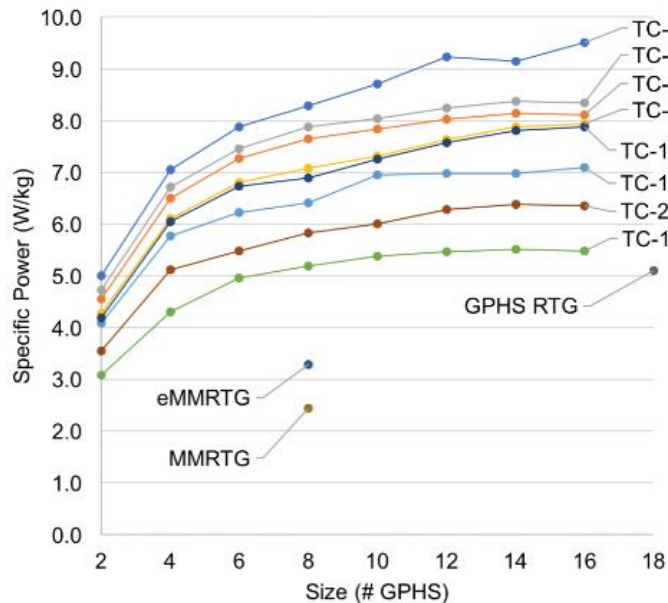
10,000 miles from Pluto

Water ice hills are floating in a sea of frozen Nitrogen

What's Next: We generally need more power – higher power RTG's
for future NASA Deep Space Missions

Next-Generation RTGs for NASA – *Concepts*

- Types of *new* RTG Concepts:
 - Vacuum Only
 - Segmented (TECs)
 - Cold Segmented
 - Segmented-Modular ★
 - Cold Segmented-Modular
 - Vacuum and Atmosphere
 - Hybrid Segmented-Modular
 - Cold Hybrid Segmented-Modular
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS
 - Output Voltage ~34 Vdc
- Typically, NASA spacecraft power busses have been designed to operate in the range of **22 to 36 V**.
- A two-GPHS unit was determined to be the **smallest SMRTG variant** capable of supporting the necessary number of TECs to meet the specified voltage requirement.
- This basic architecture would be electrically **integrated in parallel** for larger variants, such that the smallest (two-GPHS) variant determines the output voltage.



Pre-Decisional Information
-- For Planning and
Discussion Purposes Only

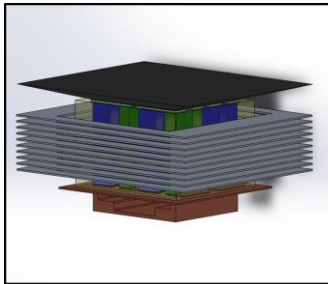
Next Generation RTG – Thermal Design Challenges

• Objectives:

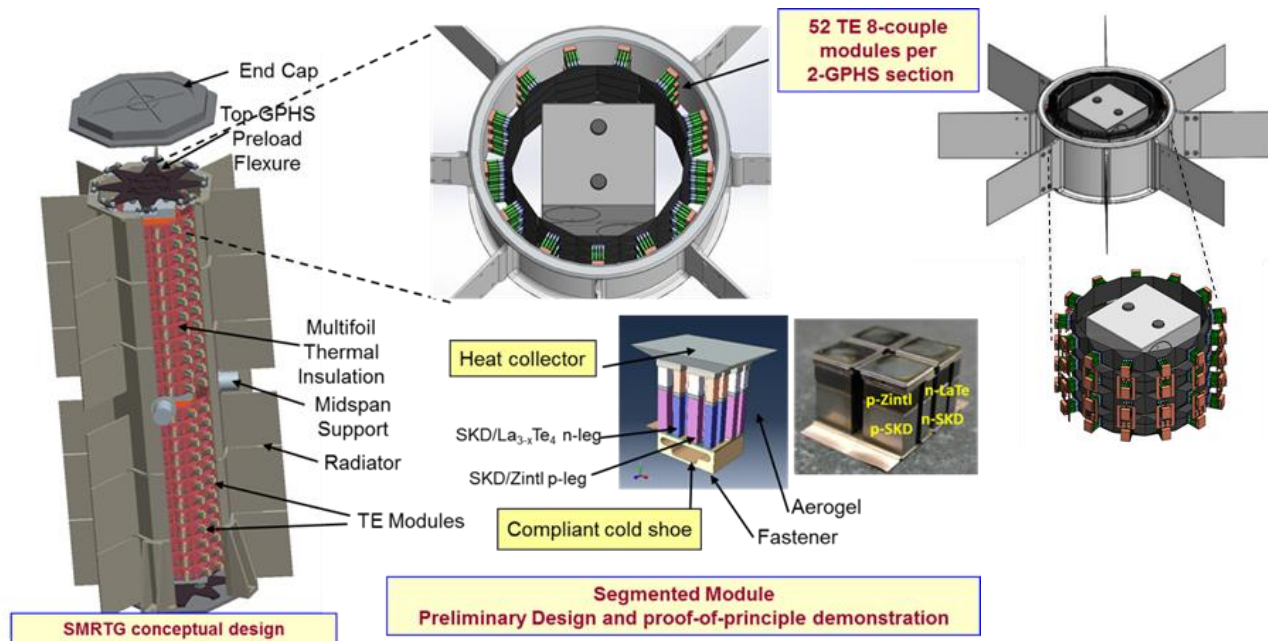
- Develop and mature advanced thermoelectric converter technology for infusion into a Next Gen RTG capable of :
 - 400 to 500W BOL power output when using 16 GPHSs
 - 10.0 to 12.5% system conversion efficiency (55 to 95% improvement over GPHS-RTG at BOL)
 - ≥ 6.7 -8.3 We/kg specific power (< 60 kg weight) (2-3 x improvement over MMRTG)
- Prediction of 1.9%/year or lower power degradation average over 17 years (including isotope decay)
- Next Gen RTG Qualification unit delivered by 2028

• Thermal Design Challenges

- Hot Side Radiative Design
- Cold Side Cooling Design
- Thermal Insulation Design



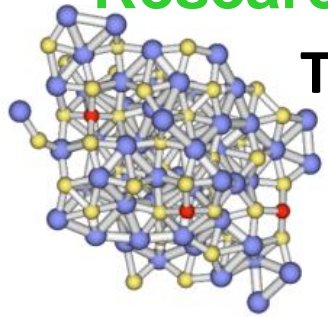
PRE-DECISIONAL INFORMATION – For Planning Only



Next Gen RTG Development Lifecycle



Fundamental Research



TRL 0-2

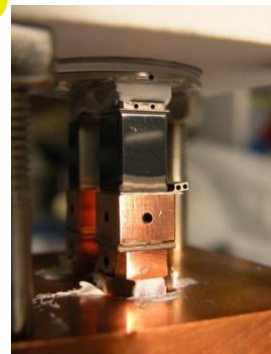
High ZT TE materials
Screening for Device Tech

Applied R&D

TRL 2



TE Materials scale-up
Element Tech Development



TRL 3-4

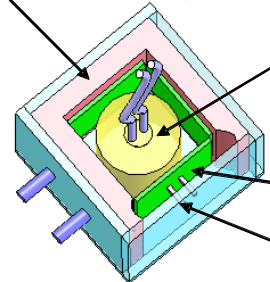
Low fidelity device development
Performance Validation & Initial life testing

NASA/Academia

NASA/Academia/Industry

TRL 3-4 Tech Maturation

Thermal Insulation

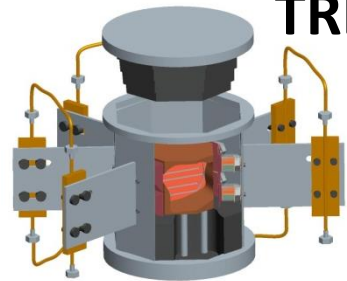


Electrical Heater

Heat Collector

T/E Couple

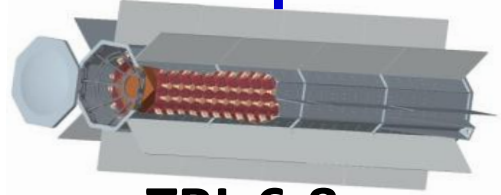
TRL 5-6



Subscale Converter Development
Life Performance Validation

EU & QU Development

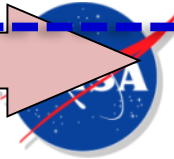
TRL 6-8



Engineering & Qualification RTG
development & performance validation

NASA/Industry/DOE

DOE/Industry/NASA





Challenge: Thermal Control for Deep Space Small Spacecraft

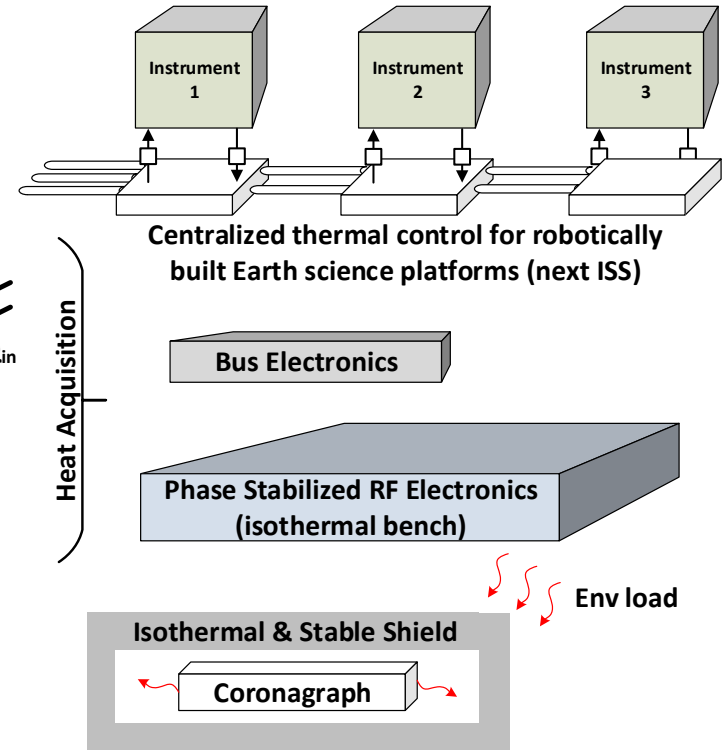
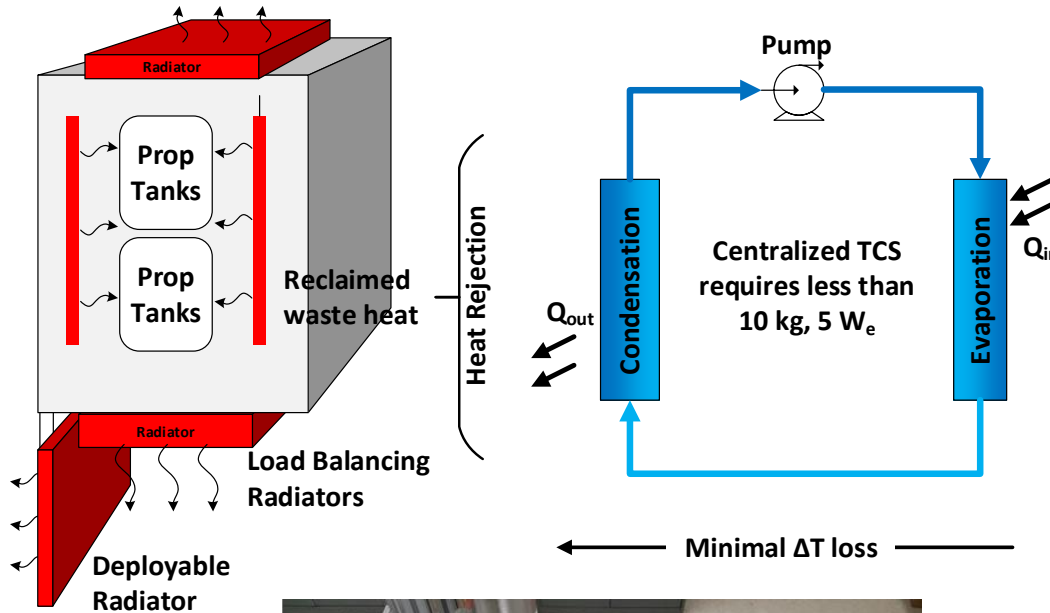
- Objective: Develop a thermal bus system (spanning both the bus and payload interfaces) that enables deep space exploration to 10 AU at low cost
- Needs
 - Order of magnitude reduction in TCS power and 50% reduction in mass over current state-of-the-art.
 - Accommodates heat fluxes up to 5 W/cm²; isothermalization of < 3 °C over a 1-m payload bench; temporal stability of < 0.05 °C/minute.
 - Modular, scalable, configurable to enable integration flexibility and at reduced costs.
 - High degree of control authority to reduce uncertainty and thermal testing costs.

Performance Parameter	SOP Large Sat	SOP CubeSat	Proposed Small S/C (~ 250 kg dry)
Cooling Load (W_t)	500	30-50	> 500
Thermal - Mass (Kg)	75 - 100	< 0.5 kg	10
Thermal - Power (W_e)	100 - 300	< 5 W	5
TRL	9	9	3

Thermal Control for Deep Space Small Spacecraft— Two-Phase Mechanically Pumped Fluid Loop Development (2- ϕ MPFL)



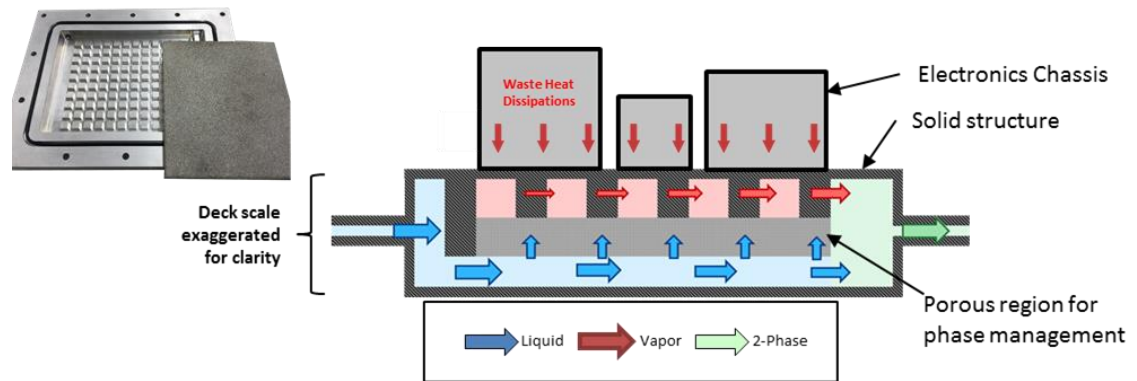
Variable Heat Rejection (Turndown)



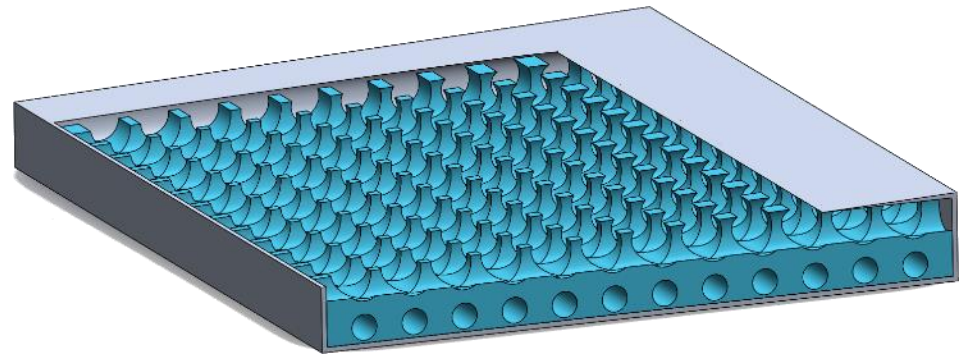
Sub-scale testing at JPL

Multifunctional Thermal Structure – Innovative Two-Phase Cold Plate

Traditional 2 ϕ heat exchangers require lengthy and separate materials procurements, fabrication, and assembly.

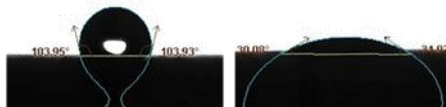


An AM fabricated aluminum wick absorbing water.

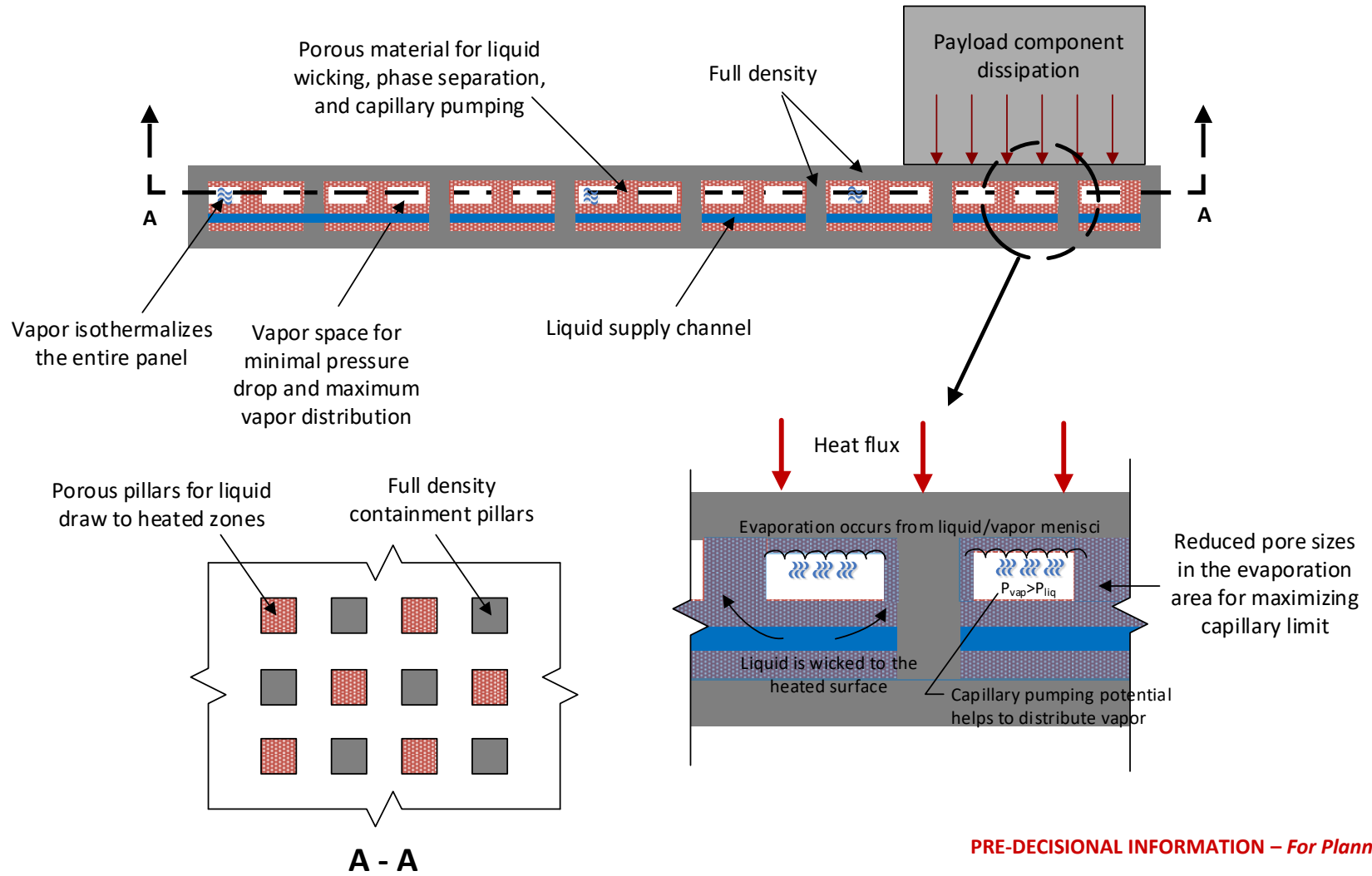


Novel cold plate designs can be created with variable porosity structural elements and open liquid passage ways to decrease mass and improve performance

Additively manufactured porous media



Multifunctional Thermal Structure – Innovative Two-Phase Cold Plate (cont'd)



The ability to additively build variable porosity structures opens a new domain space for two-phase heat transfer devices

Emerging microgap cooling to be tested aboard Blue Origin New Shepard

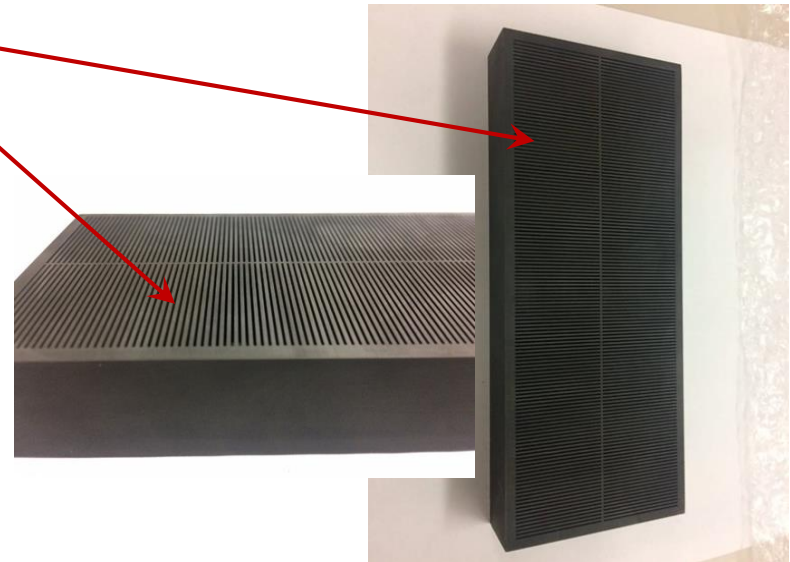
- NASA's Goddard Space Flight Center in Greenbelt, Maryland
- Cooling tightly packed, high-power integrated circuits, power electronics, laser heads or other devices.
- Operate under all conditions, including the microgravity environment found in space
 - determine is how small the channels must be to achieve gravity independence
- In microgap cooling, heat generated by electronics and other devices is removed by flowing a coolant through embedded, rectangular-shaped channels within or between heat-generating devices.
- Flight experiment also features "flow boiling," where, as its name implies, the coolant boils as it flows through the tiny gaps.
- Demonstrate for the first time during an upcoming suborbital flight aboard a reusable launch vehicle - fully reusable Blue Origin New Shepard launch vehicle



Graphite Heat Exchanger Technology

Challenge: High Performance Heat Exchange Technology for Terrestrial and Planetary Energy Recovery and Thermal Management

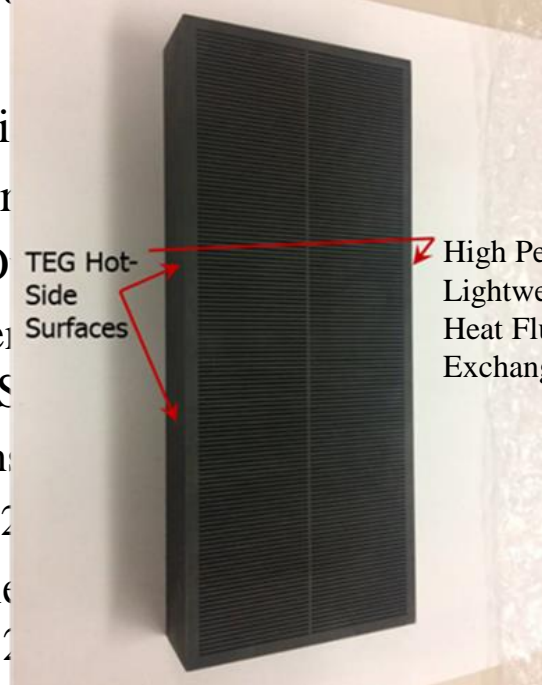
- **Demonstrated Minichannel Graphite Heat Exchange Technology @ JPL**
 - Minichannels shown to right
 - Could be gas or liquid HEX
- **High Temperature Heat Exchange**
 - 500 μm channel widths
 - 4.8 $\text{W}_{\text{th}}/\text{cm}^3$
 - Low Density, Light weight - 128 grams
 - High Thermal Conductivity
 - Low CTE
 - Reasonably good strength
 - Good manufacturability



Looking to additively manufacture this unique structure
This represents the innovative focus that is required to move micro- and mini-scale heat transfer technology into main stream

Terrestrial Waste Energy Recovery

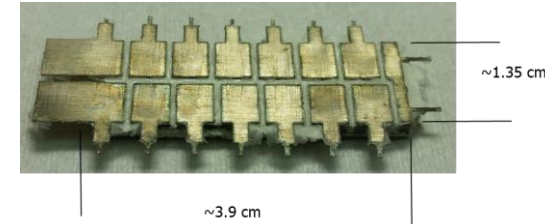
- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:
 - Energy Savings
 - Environmental Savings
 - Maximizing Conversion Efficiency
 - Maximum Power Output
- However, JPL is Currently Focused on Maximizing System-Level Performance Metric is Maximizing System-Level Performance
- Knowing Its Relationship to System-Level Performance is Key
- $T_{\text{exh}} = 823 \text{ K}$; $T_{\text{amb}} = 293 \text{ K}$
- In Addition, Key Barriers to Widespread Adoption are High Cost (As Discussed in 2010)



TEG Hot-Side Surfaces

High Performance, Lightweight, High Heat Flux Heat Exchanger

High Performance, High Power Flux Skutterudite TE Module Technology



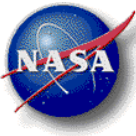
Signs Where the Critical Design

Efficiency Points is Key

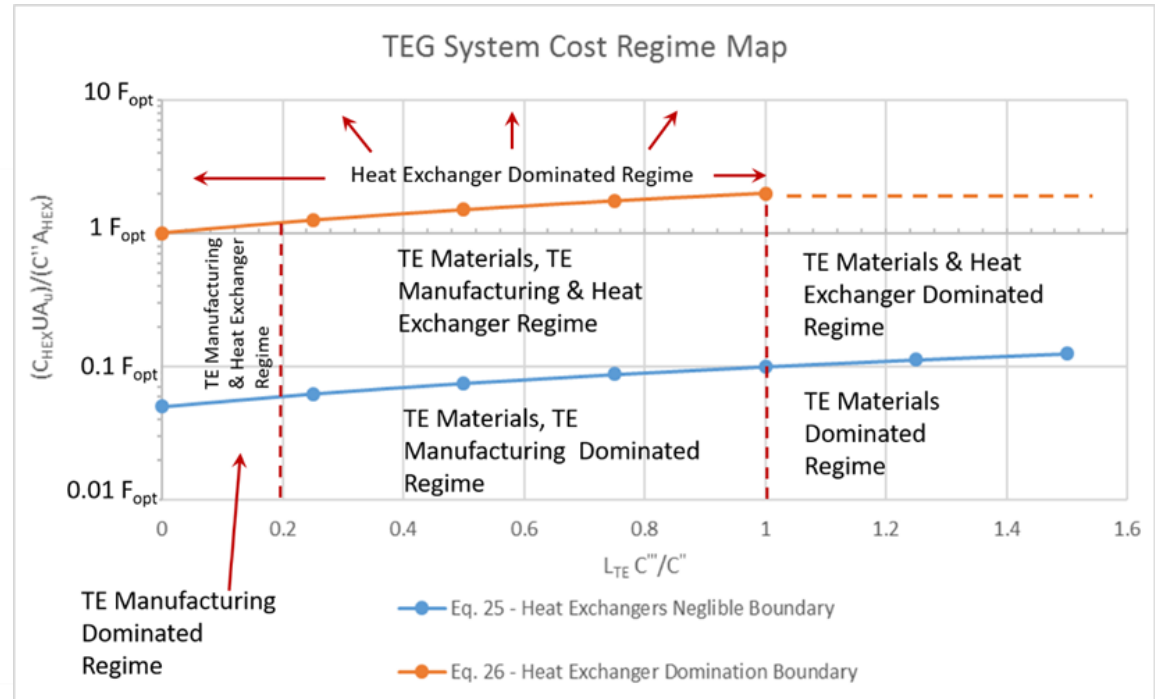
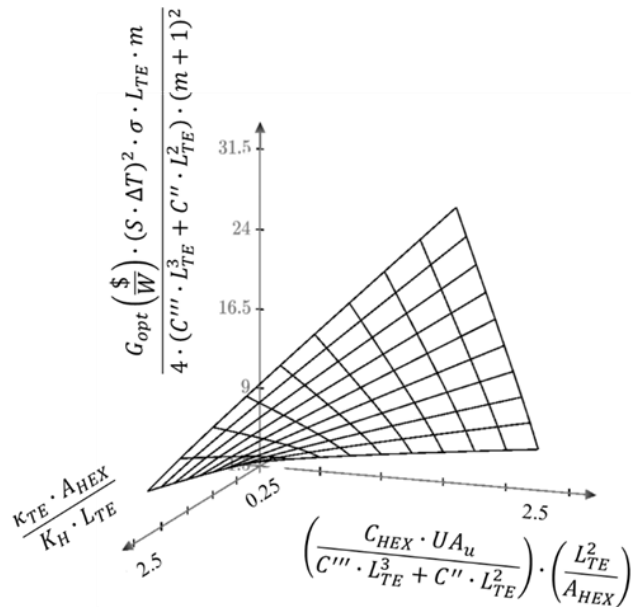
Performance Anymore as System-Level (y)

Cost Modeling and Integrating Cost Modeling With System-Level Performance Modeling is Critical

Laws of Thermodynamics /Heat Transfer & Economics Intersect



- Thermoelectric Generator Systems - If we work hard enough and long enough we can discover the intersection between the laws of heat transfer and thermodynamics and the laws of economics in our energy conversion systems – WE must!

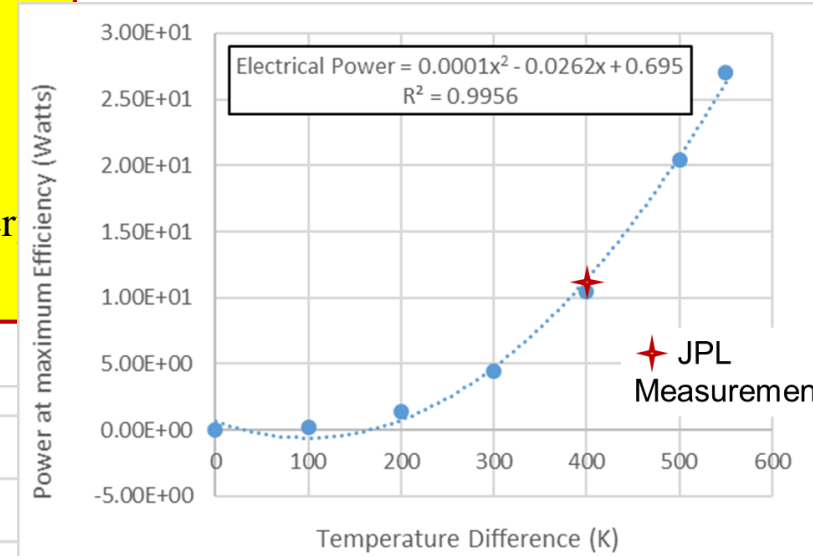
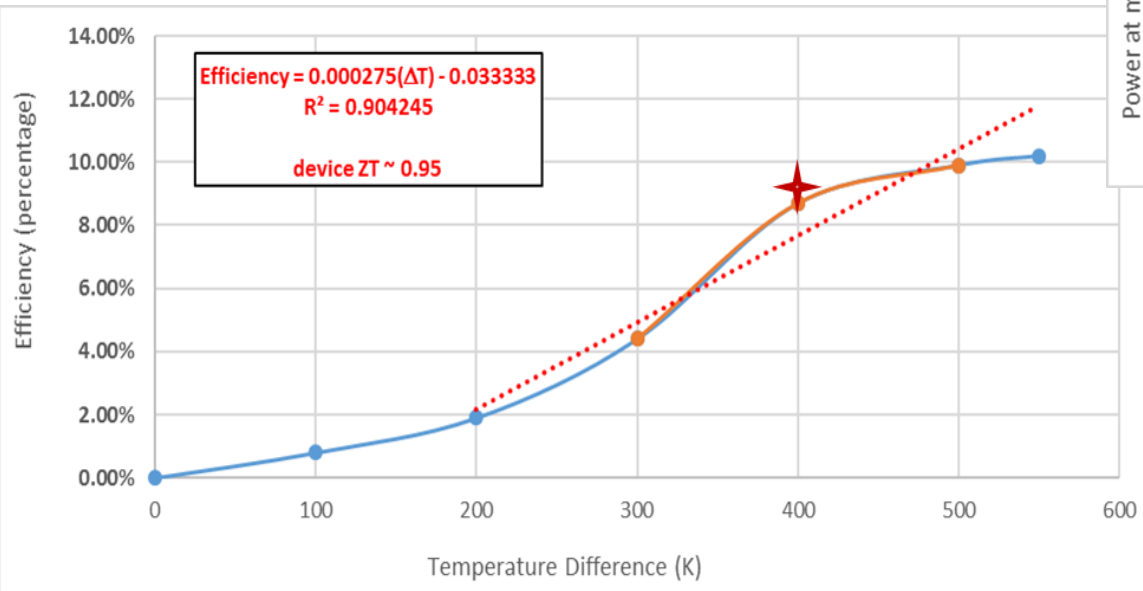


Hendricks, T.J., “Heat Exchanger Performance Impacts on Optimum Cost Conditions in Thermoelectric Energy Recovery Design”, 14th European Conference on Thermoelectrics (Lisbon, Portugal), *Journal MaterialsToday: Proceedings*, Elsevier Ltd., www.sciencedirect.com, Paper # MATPR4597, DOI: 10.1016/j.matpr.2017.12.284, 2017.

Hendricks, T.J., “New Paradigms in Cost Optimization of Thermoelectric Energy Recovery Systems”, 15th European Conference on Thermoelectric (Padova, Italy), *Journal MaterialsToday: Proceedings*, Elsevier Ltd., www.sciencedirect.com, 2018. Under publication review.

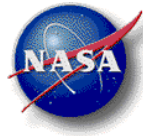
High Power Density TE Module Technology

- All-skutterudite module technology demonstrated
- High efficiency TE module demonstrated
- High Power ➡ High Power Density TE module demonstrated
- Highest power density demonstrated to date
- Exactly what is needed for various terrestrial energy recovery applications



JPL is ready to work with industry to commercialize this technology

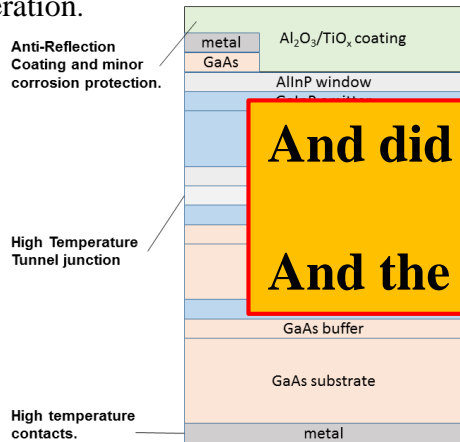
High Temperature Photovoltaics for Venus Atmosphere



Jonathan.Grandidier@jpl.nasa.gov

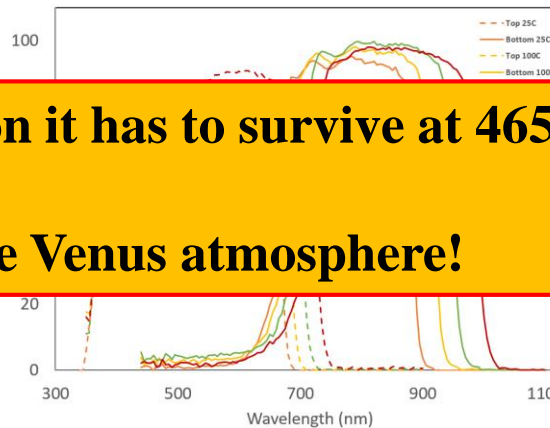
Objective: Development of a Low-intensity high-temperature (LIHT) solar cells that can function and operate effectively in the Venus atmosphere (~300°C and 100-300 W/m² solar irradiance conditions).

Simplified cross-section schematic of a GaInP/GaAs 2J solar cell designed for high temperature operation.



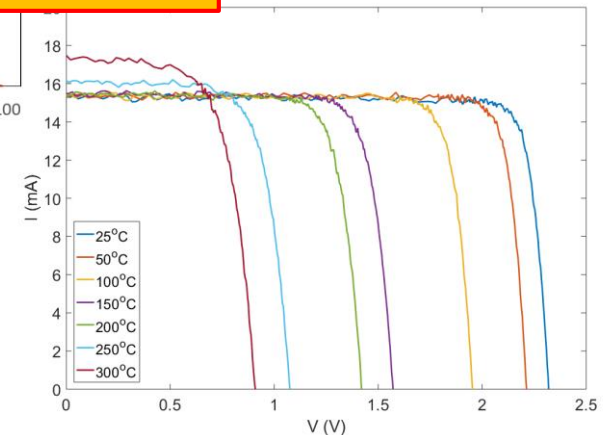
And did I mention it has to survive at 465°C too!!

And the corrosive Venus atmosphere!



External Quantum Efficiency (EQE) measurement of a solar cell (Top junction and Bottom junction) between room temperature and 100°C

Current-Voltage (IV) measurement of a solar cell between room temperature and 300°C



JPL test capability simulates Venus temperature conditions

Solar cell modeling under the atmospheric conditions of Venus used to guide the ideal solar cell structure design – Current density matching of both layers

GaInP/GaAs 2J solar cells have initially shown promising performance under high temperature characterization

Grandidier et al., (2018) “**Solar Cell Analysis Under Venus Atmosphere Conditions**”, 2018 45th Solar Photovoltaic Specialist Conference, Waikoloa, HI. In Preparation

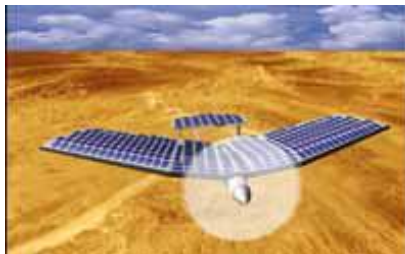
Potential Missions for Venus Explorations

- Extreme environments
 - Not habitable for human
 - Very hot environment (465°C)
 - Sulfuric acid environment
- Venus' high surface temperature overheat solar cells & electronics in spacecraft in a short time (~1 hour)
- Potential Venus Missions – Aerial and Surface Missions
 - Venus Design Reference mission
 - Venus Climate Observer (planet C) – Japan Aerospace Exploration Agency (JAXA)
 - Venus Express – European Space Agency (ESA)
- Want to determine what is there
 - Surface Heat Fluxes
 - Strong magnetic fields
 - Possible life in the extremely hot environment?



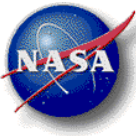
Image of the planet taken by the Pioneer Venus Orbiter in 1979

Computer Simulated Global View of Venus



Examples of Venus aerial and surface mission concepts

Biosensors - What is NASA/JPL Looking For?



The answers to these questions:

- Is there life elsewhere in the Universe?
- What is the future of life on Earth and beyond?

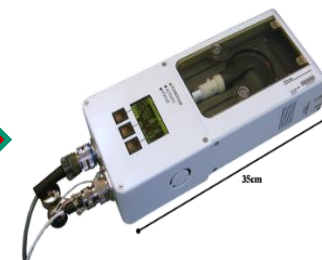
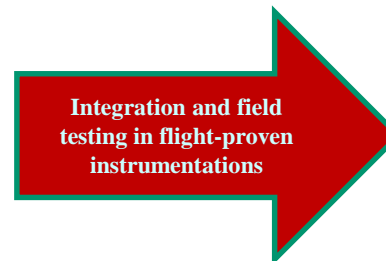
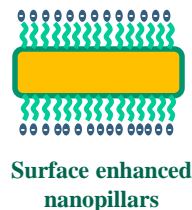
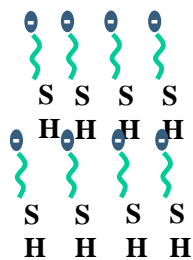
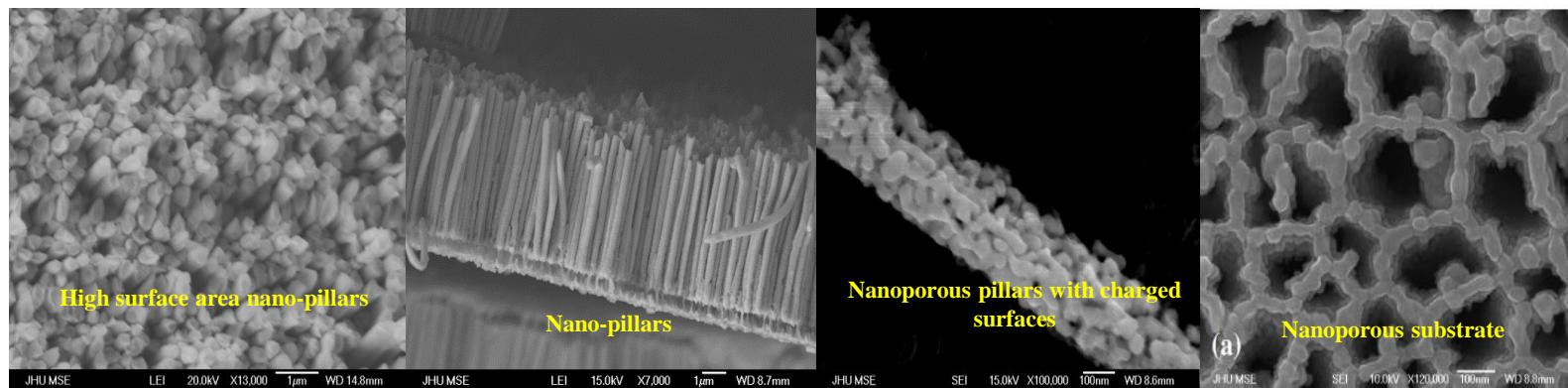
NASA's Habitable Worlds Program

- To identify the potentially habitable environments in the Solar System and beyond
- To explore the possibility of extant life beyond the earth
- Established the NASA Astrobiology Institute (NAI) to develop the field of astrobiology and provide scientific framework for future planetary exploration missions



“When it comes to extraterrestrial life, no longer is the main question whether bodies like Mars or the outer Solar System’s icy moons could be habitable. Rather, researchers have moved on to determining how they can find evidence of life, past or present, through the [presence of bio-signatures and other techniques](#).” Astrobiology Science Conference (AbSciCon) 2017

Our Technology Development Approach

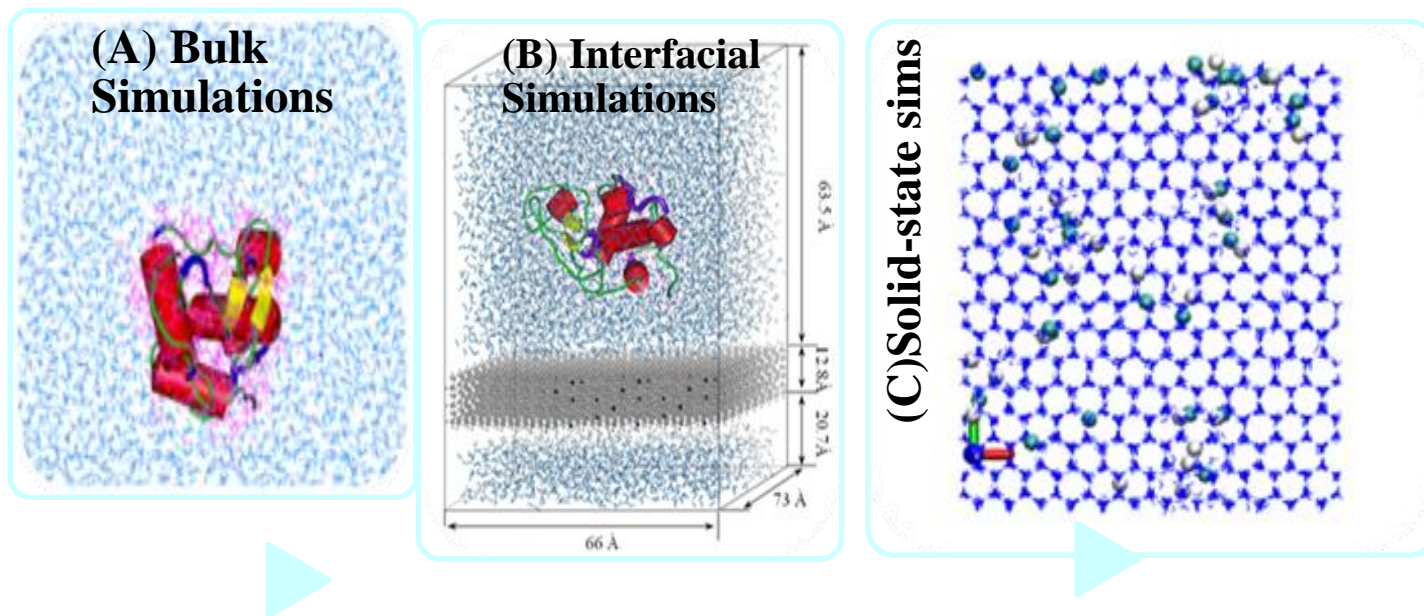
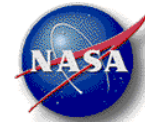


- Novel engineered nanostructured electrodes can be **retrofitted** into spacecraft-proven sensing platforms
 - Enhanced surface area of the substrate to **~1000 m²/g**
 - Electrode materials:
 - Au, Ag, Cu, Pd, Pt, shape memory alloys (SMAs), Ti-based alloys, CoCr alloys, and doped or un-doped biocompatible semiconducting materials
 - Tailor the surface porosity and morphology using various techniques
 - Enhance sensitivity and selectivity

Keith.B.Chin@jpl.nasa.gov
Ike.Chi@jpl.nasa.gov

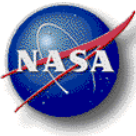
PRE-DECISIONAL INFORMATION – For Planning Only

Molecular Modeling and Atomistic Simulations Supporting Electrochemical Biosensors

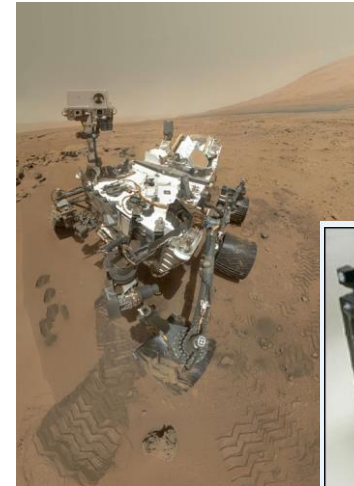


- JPL and academia collaborative efforts are underway to develop critical chemical/physical mechanisms in support of developing electrochemical sensor technologies
 - Bulk transport properties
 - Interfacial electrode/electrolyte properties
 - Charge-transfer properties

Let's Keep the End Goal in Mind – Real-World Thermal Systems

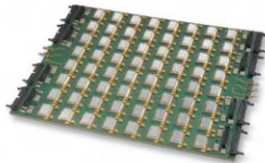


➤ Scale-Up to Macro-Sized Systems

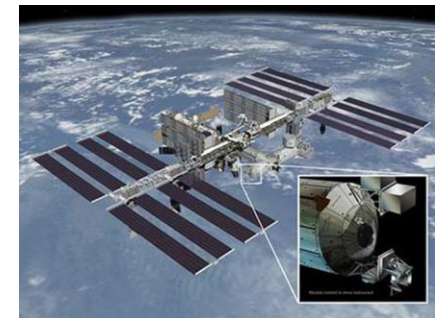


CubeSat's

Volume: ~1ft x 1ft x 1ft



Examples of Real-World Thermal Systems With Challenging System Requirements



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Picture of Earth from Cassini at Saturn